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ABSTRACT

The objective of this project was to modify an existing snowmobile to reduce emissions and noise, while maintaining or improving performance. Existing technologies and commercially available products from various engineering fields have been combined to create a finished product that suits these objectives. A single-cylinder SI engine, intake, exhaust, as well as snowmobile body modifications were made, including high flow filters, ceramic coatings, catalytic after-treatment, cowl design, and implementation of an engine management system. The finished product is an easily manufactured snowmobile that meets these objectives and can be used in National parks and other environmentally sensitive areas.

INTRODUCTION

The University at Buffalo's entry into the Clean Snowmobile Challenge offered an exciting opportunity to improve the quality of snowmobiles. A major issue in the snowmobile recreation industry has been to reduce the amount of exhaust emissions and noise output that are traditionally associated with two-stroke engines, in order to continue using the sleds in environmentally sensitive areas, without sacrificing the performance that riders expect. Given these considerations, improvements have been made to the noise, fuel economy, cost, and durability of a snowmobile that would be ideal for an average consumer. To achieve these results, a cleaner and more reliable four-stroke engine from a Polaris Sportsman 500 was selected as the power plant. This engine is liquid cooled and is electronically fuel injected using an engine management system that is currently in production. In addition, a catalytic converter was implemented to help further reduce the emissions.

ADDITIONS TO THE SNOWMOBILE

Ceramics

The internals of the engine were coated with a .002" thick Thermal Barrier Coating (TBC). Coated parts include the cylinder head, valves, exhaust ports and the upper surface of the piston. The TBC improves efficiency, longevity, and power of the engine. The TBC prevents heat transfer out of the combustion chamber resulting in better engine efficiency by encouraging proper combustion propagation and eliminating hot spots. The resulting hotter gasses help promote faster catalyst light off and help reduce emissions. The TBC also reduces weakening effects caused by heat dissipation through the engine internals, and enable the engine to withstand hotter combustion temperatures, enhancing performance.

Cooling

The sled is cooled by two heat exchangers located underneath the side running boards. The side location was chosen rather than an under tunnel heat exchanger because it would undesirably inhibit the track and suspension travel characteristics of the sled. Heat exchangers were used rather than a radiator because the cowl of the sled is sealed, rendering an under-hood radiator useless. Heat exchangers also eliminate the need of the electric fan often associated with radiators, helping to further reduce noise.

Cooling Mount Points

The supplied factory sled came with a fan-cooled engine, however there were designated areas in the engine compartment meant for implementation of heat exchangers if the chassis were to hold a liquid cooled engine. By mounting running board heat exchangers, pre-designed mounting points and pipe cut out locations were utilized. The use of these pre-existing points allowed for complete compatibility with the tunnel and suspension system.

Engine Plate

Changing from a two cylinder to a single cylinder engine required new accommodations to the chassis in order to have secure mounting points for the engine. A new engine plate was created that fit within the limits of the old plate and chassis, as well as accommodated the engine mount points of the new engine. The engine plate was constructed of ¼-inch aluminum and reinforced with gussets, ensuring high strength and prevention of failure. The design was kept simple, so production costs will be kept to a minimum. In a production version, this engine plate would easily replace the two cylinder mounting plate without adding cost.

Fuel System

Fuel to the injector is supplied via an in-tank fuel pump module. The system is a prototype model modified to fit the OEM gas tank provided. The system consists of a pump, regulator, filter and mounting/connecting plate. The system is very similar to those used in cars. The regulator is set up in parallel with the injector to allow for the appropriate pressure in the fuel lines. An in-tank system is appealing because it eliminates the hassles of running return lines and vents by enclosing these all within the fuel tank. The prototype system is also very compact and light so that it does not significantly affect the weight or volume of the fuel tank.

Hood

After installing the new engine and mounting the accessories for the engine, the hood needed to be modified. Once again appropriate modifications were selected that allow utilization of most of the OEM parts available. The new hood design calls for a closed cowling that is 4" taller than the original hood. To make the most use out of the available hood, the top portion of the hood was cut away from the bottom portion. This allowed for use of the same lighting and windshield from the original sled. Additionally it allowed retention of the mount points and style as the original.

Four inches of height were added in the center of the hood. In addition, the hood was sealed from the elements. This was all accomplished through the use of an epoxy hardened Kevlar fabric with support bracing added at critical junctions. The Kevlar-epoxy hood makes for a durable yet light protection for the snowmobile and a solid foundation to decrease engine noise.

Oil

The oil system in the sled is a gravity-fed, dry sump system that comes standard on the Polaris Sportsman 500 engine. The oil reservoir was custom made of 1/8-inch aluminum and holds two quarts of fluid. The reservoir was mounted above the engine so as to provide gravity-induced flow during steep uphill climbs. The oil in the sled is a lightweight synthetic and was selected to avoid reduction of the engine's performance due to viscosity. The oil is plumbed through large, 3/8-inch rubber hoses because the original hoses were not designed for the extremely low temperatures that snowmobiles experience.

Steering Modification

A steering modification was needed to avoid a conflict between the new engine plate and the preexisting steering rods. Since one of the engine mounts is located directly above the steering setup the engine mounting bolt and steering rod would have collided around corners. Also, when the front suspension was in compression, the steering rods would have tried to force the engine mount up and out. To solve this problem, a simple solution was developed that only slightly changed the steering setup. By adding a 1-inch long billet aluminum spacer onto the steering bell crank, the steering rods were lowered to a point where they do not hit the engine mount. In a production version, this spacer-bell crank combination could be replaced with a bell crank with a longer drop to the steering rods. By lowering the interior points 1-inch, a serious problem was avoided, and kept the steering within production constraints.

ENGINE, MECHANICAL SYSTEMS

Assumptions

After reviewing the rules and determining the main objective of the competition, it was decided that the best power plant to use was a four-stroke engine. Two-strokes are traditionally noisy, inefficient, and have unacceptable levels of exhaust emissions. These characteristics are due to relatively high engine speeds, engine oil combusted along with fuel and air, and poor port timing with respect to fuel metering [7]. To alleviate these problems quickly and easily, a four-stroke engine was installed. The presence of physical valves, as opposed to ports, opening and closing of which are dictated by piston position, enables far superior control over the fuel-air mixture entering and leaving the engine. Further refinement in fuel metering was achieved by implementing an electronically controlled engine management system. Refining the fuel mixture control into the engine and separating the fuel and oil increases efficiency and reduces exhaust emissions. Finally, this four-stroke is designed to run at lower engine speeds than its two-stroke counterpart. This has a positive effect towards reducing noise and improving fuel consumption.

Required Modifications

The Polaris Sportsman 500cc engine was selected for use in the Polaris Indy Trail snowmobile chassis. This engine is similar in weight to the stock engine resulting in little need in suspension to maintain stock performance in handling. Mounting the new engine proved to be a formidable obstacle due to the need that it be mounted at a 45-degree angle without modifying the bulkhead. This task was accomplished by creating a detailed AutoCAD file then using the said parameters to form a plate that could do the job. The result is a ¼-inch thick aluminum plate needing only three bends that mounts to the sled using two existing holes and requires the addition of two new holes. The plate is mounted rigidly to the bulkhead while the engine is mounted to the plate with ¾-inch rubber dampers.

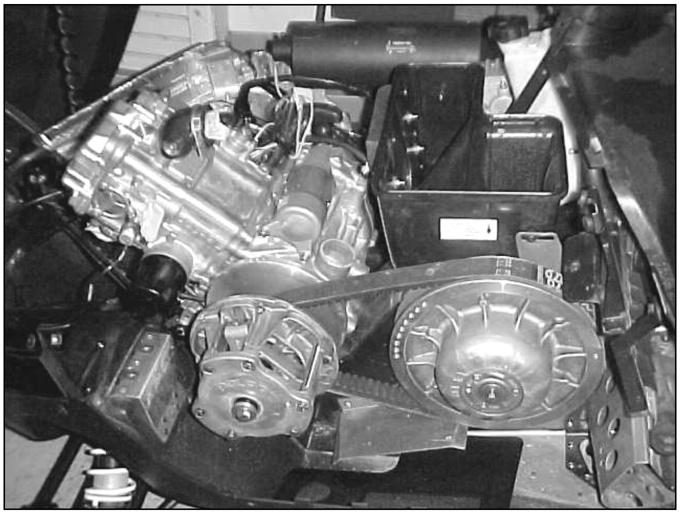

Figure 1.0 demonstrates the severe angle at which the engine sits in the snowmobile.

Additional systems had to be retrofitted onto the sled to account for the characteristics of the new power plant. Additional systems include:

- Non-loss oil system;
- Liquid coolant system;
- Four stroke exhaust;
- Engine management system;

University students conducted the following engine refinements at the Truco engine facilities in Buffalo, New York.

Internal improvements include:

- 5-angle valve seating;
- Valve refinishing;
- Stem refinishing;

In the production engine these post production refinements will not be necessary because the processes and quality controls will be already in place for the initial production.

Impact on Fuel Economy

As expressed later in greater detail, the addition of fuel injection to the sled, coupled with the efficiency of a four stroke engine results in enormous fuel economy gains.

By refinishing the internals of the engine, better mileage from the sled can be expected. Although not as noticeable as the gains brought about by the fuel injection, the fine-tuned valves and polished ports enhance airflow through the engine, increasing volumetric efficiency.

Impact on Emissions

The switching of engines from a 2-stroke to 4-stoke was perhaps the most feasible method any team could have made in the efforts to reduce emissions. The 2-stroke engine utilizes a 100% oil loss system meaning that all of the engine's oil is burned with the fuel resulting in extremely high emissions. By implementing an oil system that recycles the oil through the engine, harmful by-products associated with burning oil are greatly reduced. The four-cycle engine separates the intake and exhaust strokes so that the incoming air fuel mixture is not expelled prior to combustion. By preventing fuel waste the engine is inherently cleaner. This in turn, leads to a more effective catalyst since it is able to burn up a larger percentage of the wasted fuel since there is less fuel per volume entering the catalyst at any time. Another way to keep the heat up, and subsequently reduce the catalyst light-off time, is to wrap the exhaust with header wrap so that the heat in the exhaust is reflected back to the center of the exhaust pipes.

Noise Impact

One of the major reasons for switching to a four-stroke engine was to decrease noise levels of the snowmobile. By using a single-cylinder 4-stroke engine, the sled can be operated at a much lower RPM, helping to reduce noise. This low operating RPM combined with the muffler and air box should keep the noise emissions to a minimum. Another aid to the muffler is the header wrap used to contain both heat and noise. Also, all metal-to-metal contacts were either rigidly mounted or damped using rubber spacers. By either fixing two parts together as one, or isolating the parts so that they cannot interact, engine compartment noise is significantly reduced.

Weight Impact

The modified sled weighs approximately 50 pounds more than the initial two-stroke sled. The additional weight is largely due to the cooling system associated with this engine. The modified sled uses a liquid cooling system, which requires a coolant reservoir, heat exchangers, hoses and fluid.

Cost Impact / Durability

Although many changes to the snowmobile and the engine have been discussed, many of these changes were merely a swap of OEM parts or simple modifications to those parts. Since as many OEM parts were implemented as possible, either from the snowmobile, or from the four-wheeler, it is believed that this design should hold up to the rigors applied to rental equipment and from first time buyers. Durability of the *integration design*, however, (and interface integrity of diverse components), cannot be evaluated until competition.

The main disadvantage to the engine set up is the added cost due to added production time because of new small steps added into the sled's production. Whether or not changes ceramic coating the interior engine parts make a significant difference needs to be seen in competition. If the changes are absolutely necessary then they are worth the cost, however if few gains are observed, then they can be considered optional steps in the final production of the snowmobile.

Performance

Steps have been taken to ensure that the most power can be transferred from the engine without putting it at risk of failure. The ceramic coatings of the engines internals as well as the liquid cooling system will allow the engine to be run leaner and hotter resulting in more power. In addition, the small details, such as the valve improvements, will allow fluids to pass through the engine as smoothly as possible, which in turn will help create more power.

ENGINE MANAGEMENT SYSTEM

Assumptions

An electronically-controlled engine management system was selected for this application primarily in order to maintain precise control over fuel metering and spark advance. Use of such systems allows for refined calibration of the *entire* operating range of the engine, a necessity when developing a low emissions output, high fuel economy application utilizing a catalytic converter [1].

The engine management system selected is produced by Magneti Marelli USA of Farmington Hills, Michigan, and is currently in production on Harley Davidson motorcycles. This system was selected for the following reasons:

- Configurable for a 1 or 2 cylinder application;
- Alfa-n style controller (TPS/RPM dependent maps);
- Closed-loop control capability;
- Mature cold start routines;
- Ambient altitude compensation;
- Ambient temperature compensation;
- System donated to team for CSC 2000 competition;

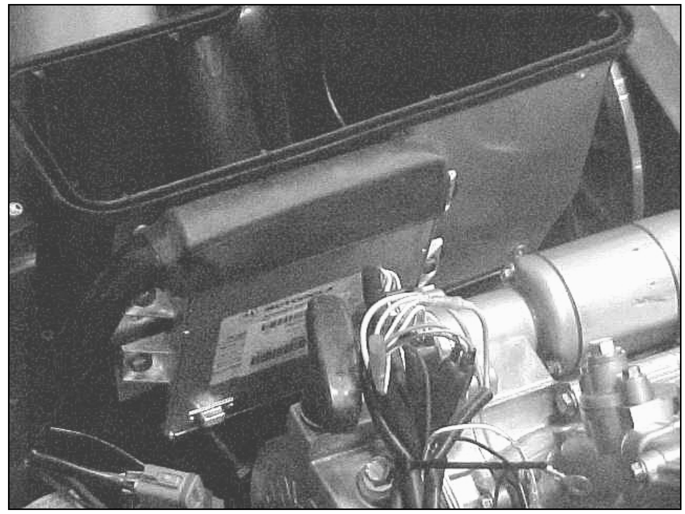

Figure 2.0 shows the Magneti Marelli ECU as mounted in the snowmobile.

Required Modifications

Few intrusive modifications were required to retrofit the Magneti Marelli system to the 500cc Polaris engine. The system itself requires several inputs, including crankshaft speed, camshaft position, ambient air temperature and pressure, engine temperature, and throttle position. Additionally, it may be configured to receive exhaust gas information via an oxygen sensor when using a catalytic converter, which is the case for this sled. Figure 3.0 shows a block diagram of the basic system I/O architecture.

The crankshaft speed information required the implementation of a ferrous tone wheel on the flywheel of the engine, and the mounting of a VR type sensor (magnetic) in the lower case to read the tone wheel. The existing 1 tooth 'tone wheel' was milled down, and the new required tone wheel press fit in its place. The cam position pickup was mounted directly to the cam gear wheel, and the Hall effect sensor mounted in a newly fabricated cam gear cover plate.

Other required components (non-invasive to the engine) include:

- In-tank fuel pump module with integrated 3 bar pressure regulator;
- Oxygen sensor mounted in the exhaust pipe up-stream of the catalytic converter;
- A throttle body with integrated throttle position (TPS) and air temperature (ATS) sensors;
- An adapter to connect the throttle body to the Polaris intake port, including a mounting boss for a fuel injector;
- Engine temperature sensor, mounted in water jacket (existing mount from stock engine);
- Barometric pressure sensor;

- Ignition coil;
- Engine electronic control unite (ECU);
- Engine management system (EMS) wiring harness;
- Electrical connection with sled power/ignition module;
- Electrical circuit utilizing lanyard to disable spark and fuel;
- +12v motorcycle/recreational vehicle battery;
- Pd- only close-coupled catalyst (optional but used in this application);

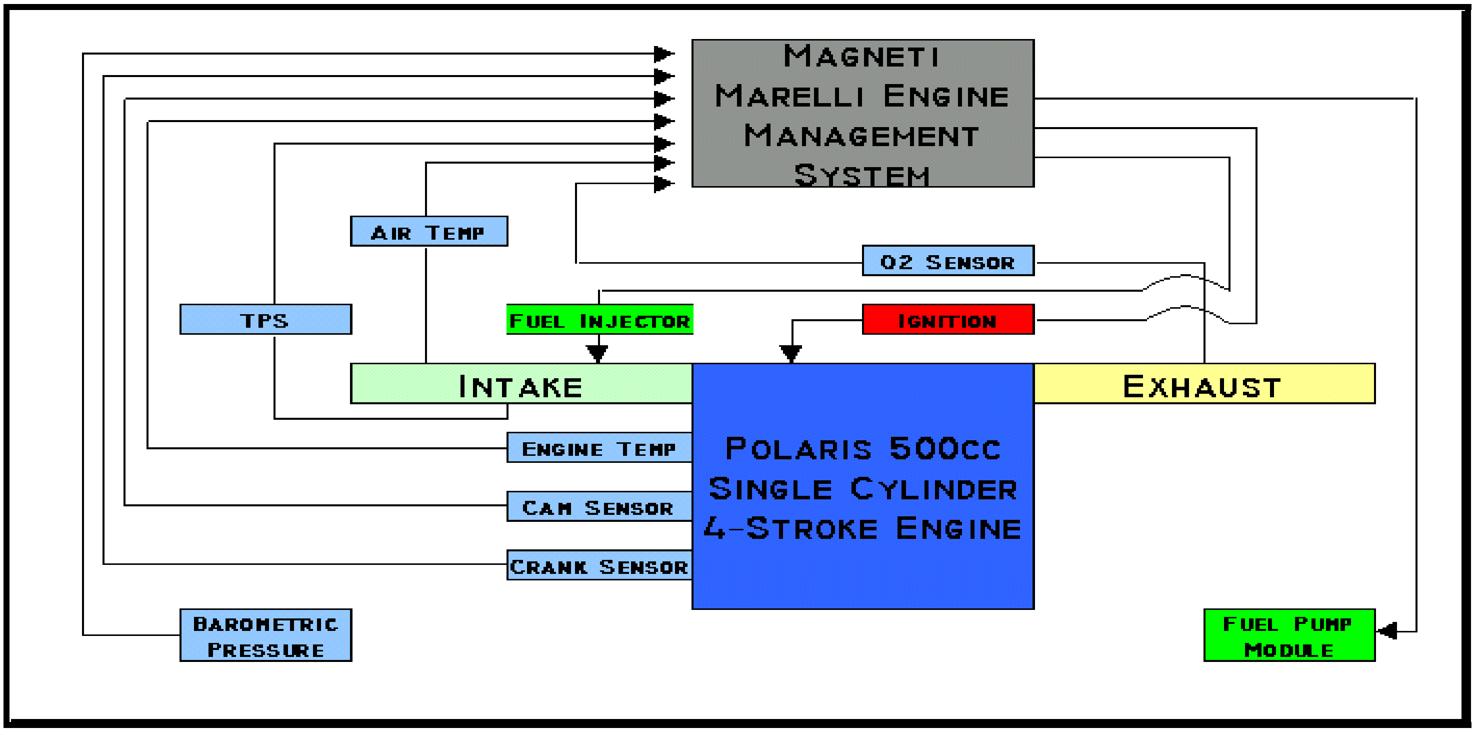

Figure 3.0 is a block diagram representing the basic system input-output architecture of the engine management system.

Impact on Fuel Economy

A properly tuned fuel injection system is vital for establishing fuel economy improvements. There are significant gains to be made by having the capability of optimizing each and every speed/load operating point, not to mention the fuel-hungry cold start. Moreover the introduction of altitude and temperature compensation, and closed loop control (via O2 sensor feedback), makes it possible to maintain tight control of the engine's behavior over the variety of environments the sled will be used in.

The expected fuel economy gain between this particular fuel-injected four-stroke engine, and its carbureted two-stroke counterpart of equivalent horsepower, over a 90-mile run, can be estimated by evaluating each engine's brake specific fuel consumption (BSFC) characteristic.

BSFC is a measure of how efficiently a particular engine uses fuel to produce a given quantity of horsepower [2]. This value for four-stroke engines with fuel injection will approximately be 0.4 – 0.55 [lbs/hp*hr], versus a carbureted two-stroke, at approximately 0.65 – 0.9 [lbs/hp*hr]. All things may be set equal for sake of comparison by assuming each engine is run at some maximum horsepower number on a 90 mile fuel economy trail, at a peak speed of 45 mph. Assuming that the horsepower is 35, the estimated gallons consumed over 90 miles are shown in Figure 4.0.

2-Stroke Carbureted	BSFC = 0.650	7.48 gallons
	BSFC = 0.900	10.36 gallons
	AVG BSFC = 0.775	8.92 gallons
4-Stroke EFI	BSFC = 0.400	4.61 gallons
	BSFC = 0.550	6.33 gallons
	AVG BSFC = 0.475	5.47 gallons

Figure 4.0 compares maximum fuel consumption estimations between 2-stroke and 4-stroke engines of equivalent horsepower over a 90-mile fuel economy trail.

Comparing average values, these estimations predict a **38.7%** decrease in fuel consumption.

Impact on Emissions

The introduction of electronic engine management control allows for the use of two strategies for reducing HC and CO. The first is lean operation of the engine during cold start and "hot modes" of operation, namely constant throttle cruises [1,3]. The second is to optimize the calibration around the fact that a catalytic converter is in the exhaust pipe.

Figure 5.0 [4] shows the influence of A/F ratio on the major exhaust gas constituents. Clearly it can be seen that operating at an A/F ratio of ~15.5:1 or 16:1 causes a significant reduction in HC and CO emissions. Certainly torque is less at these ratios than at the stoichiometric 14.7:1, however at near constant throttle cruises this becomes a non-issue, and as such this technique is commonly used for closed-loop, catalytic, port EFI applications.

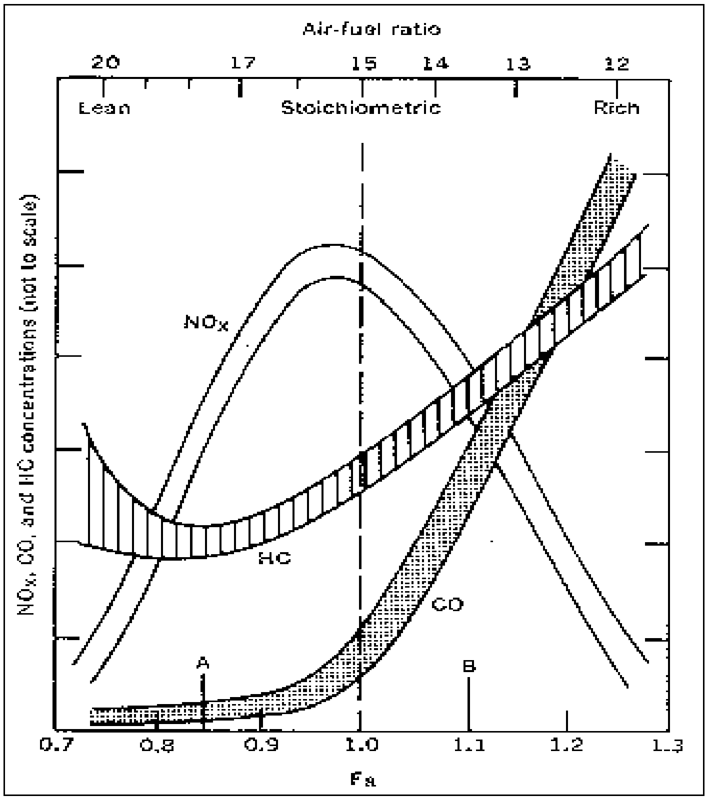

Figure 5.0 shows the influence of A/F ratio on the behavior of exhaust gas emissions concentrations.

The introduction of a catalytic converter into the exhaust circuit enables the second method of using electronic engine management control to reduce emissions. The key to taking advantage of a catalyst is to achieve catalyst light off as soon after engine start-up as possible, and to maintain light off during all operating conditions. Having a closed-loop control strategy is vital to accomplishing this second part.

In this application, a single, close-coupled catalyst strategy was utilized, which has been found experimentally to be adequate for small displacement engines [1,6,8]. A Degussa palladium-only catalyst was utilized, with a loading of 200 grams per cubic foot on a 200 cells per square inch substrate. Usage of palladium/platinum PM loading combinations, as well as palladium-only close-coupled strategies, have recently gained more popularity as more exhaust gas after-treatment studies are conducted [1,3,9]. Typically a higher palladiums loading results in higher HC conversion efficiencies at lower light-off temperatures [9].

Research studies conducted on engines of similar system architecture have shown impressive reductions in HC and CO output [6]. Introduction of a closed-loop engine management system, with a close-coupled catalyst to an engine of similar displacement and configuration, has yielded a 92% HC reduction, and a 95.3% CO reduction. Further research conducted on a larger 2-cylinder engine, of like fuel system and catalytic after-treatment architecture, yielded an impressive 89.3% HC reduction, and a 77.9% CO reduction.

The emissions reduction for this particular vehicle, while certainly difficult to predict, should keep with these findings. The assumptions made in constructing this system hold with current industry research and practice, and are directionally correct for a significant emissions reduction. Results from the CSC 2000 competition are required to make a direct comparison with current regulations for this class of engine.

Noise Impact

Introduction of an engine management system has little impact on noise. The cyclic priming of the fuel pump produces a small humming noise hardly perceptible during vehicle operation.

Potential gains could be made with respect to internal engine noise, as a result of having more refined idle operation, absence of rich-mixture misfire, and absence of over-lean mixture knock. In addition, having the catalyst in-line in the exhaust contributes heavily towards muffling emitted engine noise.

Cost Impact / Durability

For this competition, the cost impact of implementing an engine management system was minimal. The system and catalyst were both donated to the team by Magneti Marelli USA. Implementation costs include materials to manufacture the tone wheel, injector boss, throttle body adapter, cam sensor mount/cam gear cover plate, and minimal wiring to adapt the system harness into the sled. Real cost for this system is feasible, as it is presently a production system. The exact cost impact can be obtained from Magneti Marelli USA, and is dependent on volumes and application.

The system is relatively robust in terms of durability. It is in production on Harley Davidson motorcycles, which create a very harsh vibration and heat environment for the system to survive in. All components are rated to 120° C, and the engine ECU meets environmental specifications for under-hood automotive usage. Vibration could pose an issue in areas where prototype pieces have been made-to-fit, as they are untested and not validated according to any specific test procedures.

Performance

Introduction of an engine management system will inherently provide an increase in volumetric efficiency over its carbureted counter-part, due to the separation of air and fuel inside the intake runner. All things being equal, this predicts a power increase over the carbureted version [5].

Other performance gains include superior cold start and operation capabilities, enhanced transient response, and better overall drivability throughout a wide range of operating conditions.

RESULTS

The results from the CSC 2000 competition solidify this approach as an effective way to reduce snowmobile noise and emissions. The tested fuel consumption of this sled was significantly less than that of the control snowmobile. The control snowmobile burned 7.366 gallons of gas during a 90-mile trail ride, compared to 3.237 gallons consumed by the University at Buffalo sled. In terms of fuel economy these numbers indicate 12.2 mpg for the control sled compared to 27.6 miles per gallon for the University at Buffalo sled, a 127% improvement.

The results for the emissions reduction event were equally impressive. The measured HC emissions were below the low-end resolution of the measuring equipment, and deemed 'Virtually Undetectable'. Subsequently it was scored as a 99.5% reduction over the control snowmobile. The CO emissions reduction was not as high as predicted, nonetheless the University at Buffalo sled still achieved a reduction of 46% over the control.

The measured pass-by noise of this snowmobile was 66.8 dB at full open throttle. Of the 7 teams competing in the CSC 2000, only one other school managed to post noise levels under the 74 dB restriction (73 dB).

In general the 4-stroke snowmobile's performance characteristics met expectations. The single cylinder engine provided a very flat torque curve that yielded driveability characteristics that came as a pleasant surprise. While top speed and high-end acceleration clearly belong to the 2-stroke sleds, the abundance of low-end torque make this snowmobile a great trail rider and certainly no slouch when pulling out of deep snow. In the Hill Climb event, the snowmobile climbed to an equal elevation as five of the six other competitors. Additionally the judges, (Yellowstone fleet and tour operators), scored this snowmobile 4th place of 7 teams in the Handling event. This 4-stroke powered snowmobile clearly lagged behind its 2-stroke competitors in the acceleration event as expected, however it still achieved a time of 10.0 seconds over a 500 ft strip of packed snow, compared to the control sled's 7.8 seconds.

The University at Buffalo solution took first place honors in 5 of 6 categories at the CSC 2000, including 1st place overall (exceeding 2nd place by over 200 points out of 1000), Best Emissions, Best Fuel Economy, Quietest Snowmobile, and Best Design.

CONCLUSION/SUMMARY

Over the course of 4 months significant and exciting progress was made towards the goal of creating a cleaner and quieter snowmobile that is still suited for its purpose as an enjoyable trail sled. Utilization of existing technologies has enabled the creation of an easily reproducible sled that is environmentally conscientious, while maintaining the performance that snowmobile enthusiasts have come to expect from today's machines.

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